3.1. Textile-based Antennas

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ABSTRACT

Antennas are among the key passive components used in electronics. This paper focuses on textile antennas, which are becoming increasingly significant in the growing field of electronic textiles (e-textiles). Textile antennas can be fabricated using various technologies, resulting in a range of properties. In addition to enabling wireless data transmission, these antennas can also function as sensors for strain and mechanical deformation. A major challenge in this domain is the reliable electrical interconnection between textile antennas and other electronic components. Conventional electronic technologies are often incompatible with textile substrates, prompting the development of dedicated contacting methods suitable for e-textile applications. The paper presents several fabrication techniques and preparation methods for textile antennas, along with testing results related to their specific applications. These include not only data transmission systems integrated into garments but also sensor-based antenna structures for detecting mechanical stress, with potential use in healthcare and industrial settings.

INTRODUCTION

Currently, there is a growing prevalence of electronic textiles (e-textiles). The aim of these e-textiles is to achieve a high level of integration of electronic components into the textile structure. The fundamental building block of e-textiles is conductive threads, which enable the realization of electrode systems, resistive heating elements, sensors, interconnect systems, and passive components, including planar textile antennas.

In recent years, textile antennas have garnered significant attention due to their lightweight, flexibility, and wearability, characteristics that make them ideal for various applications such as health monitoring, data transmission from sensors in Internet of Things (IoT) devices, and other communication systems. Planar textile antennas can be created using various techniques, including the embroidery or weaving of conductive patterns with the aid of conductive threads. These technologies facilitate the development of textile antennas for data transmission as well as antennas that can function as strain sensors.

For data transmission antennas, it is crucial to design and implement antennas with a defined resonant frequency that remains invariant under mechanical stress, while also considering the positioning on the human body and ensuring durability against standard textile maintenance. In contrast, textile antennas (resonant structures) utilized as strain sensors take advantage of the flexibility of textile materials; mechanical stress results in changes to the geometric dimensions, consequently altering the resonant frequency. These characteristics of textile antennas can be applied, for example, in monitoring limb swelling, assessing respiratory rates, and even in construction for monitoring structural displacements.

Textile antennas will find application in telemedicine, wellbeing, sport or rescue systems. Textile antennas offer key advantages such as flexibility, elasticity, comfort, breathability, washability, low weight, 3D deformability, and seamless integration into clothing. Their compatibility with textile substrates enables comfortable, unobtrusive wear, making them ideal for wearable applications. Performance depends on both fabrication method and application-specific requirements. A notable benefit over other wearable technologies is breathability, preserved through the use of textile materials, except in printed antennas, where breathability may be reduced due to the printed layer.

Proper design and a well-executed manufacturing process are crucial for achieving optimal fabric antenna performance. When selecting an appropriate method, it’s essential to ensure that the design matches the simulation to guarantee robust and reproducible results. Various manufacturing techniques can be categorised as follows:

- Weaving or knitting conductive antenna patterns using conductive textile threads or yarns.
- Embroidery of conductive patterns of antennas using conductive textile threads or yarns.
- Ink and screen printing of conductive patterns using conductive pastes and inks on a non-conductive textile substrate.
- Metallization of non-conductive non-woven fabrics.

From the point of view of interconnecting technologies, it is possible to use soldering, sewing, hot bar, resistance or ultrasonic welding, adhesive bonding or thermo-compression (e-textile bonding).

This article discusses the technological aspects of producing textile antennas to ensure the desired parameters are met, presents their electrical and mechanical properties, and explores potential applications for their use.

references [1], [2], [3], [4], [5], [6], [7], [8], [9], [10], [11], [12], [13], [14], [15]

MATERIALS AND METHODS

Hybrid conductive threads

The production of electrically conductive hybrid threads allows the creation of various types of yarns combining ultrafine metal fibers (such as stainless steel, silver-plated copper, or copper-nickel alloys) with synthetic materials, such as polyester or polyamide. These conductive hybrid threads (Fig. 1) developed by VÚB Company in close collaboration with University of West Bohemia. Conductive hybrid yarns can vary in the number of microwires embedded in the yarn. Conductive threads are used to create conductive patterns for planar textile antennas using various textile technologies.

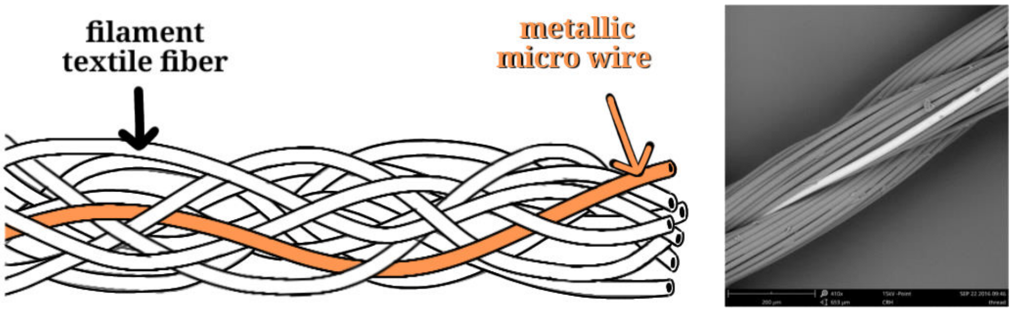

Fig. 1. Example of conductive hybrid thread

Knitting technology

Knitted textile antennas are produced directly in textile form using knitting machines with conductive fibers, offering flexibility and comfort ideal for wearable applications. Wholegarment knitting enables waste reduction, fewer production steps, and design variability (e.g., intarsia, jacquard, spacer structures). However, it involves complex and time-consuming development. Knitted antennas benefit from structural flexibility and ease of integration into textiles. Limitations include lower precision, uneven edges, and low resolution due to machine constraints (needle density, tension), potentially affecting antenna performance. Production also requires large amounts of yarn and skilled operation. Mechanical deformation during wear (stretching, bending) can alter resonant frequency and degrade performance due to material fatigue, e.g., microcracks or fiber breakage in metal threads. Knitted structures often have lower conductive fiber density and higher resistance compared to embroidery, weaving, or lamination methods (Fig. 2).

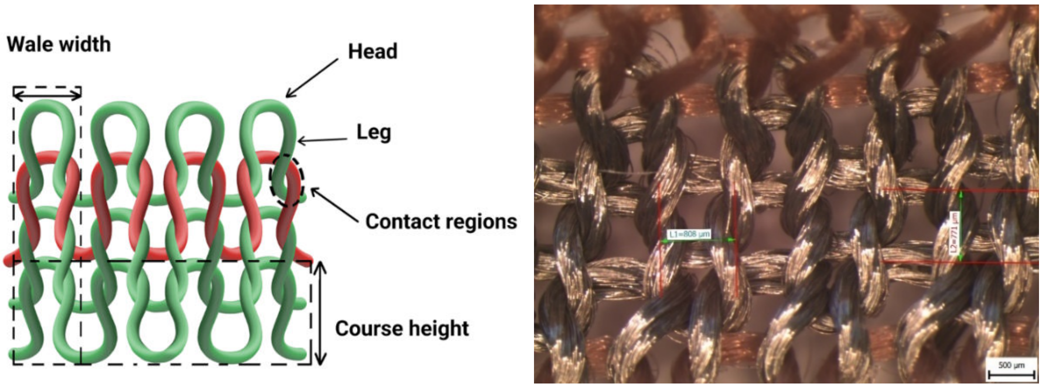

Fig. 2. Knitted textile structure

Embroidering technology

Embroidered textile antennas are fabricated using embroidery machines that enable precise integration of conductive structures directly onto textile substrates. Suitable conductive threads, such as hybrid threads resistant to friction and breakage, are essential. Substrate selection and embroidery density significantly influence antenna performance. Embroidery offers high precision and control over electrical parameters, facilitating frequency-specific designs (Fig. 3). The process is relatively simple and scalable, with production time depending on antenna size. However, embroidered antennas have limited flexibility, which can reduce comfort in applications requiring frequent bending or stretching. Fully filled embroideries, even on elastic fabrics, remain rigid. For improved flexibility, both the embroidery pattern and substrate must be designed accordingly. Rigid embroidered antennas are well-suited for applications demanding electrical stability, whereas knitted antennas are more appropriate for highly flexible wearable systems.

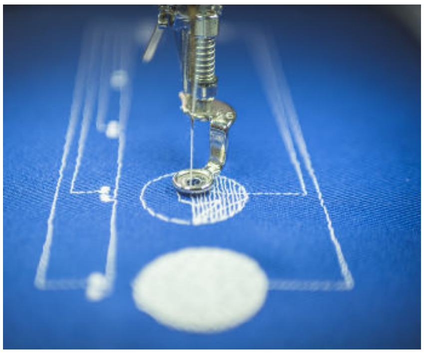

Fig. 3. Embroidering of conductive pattern

Weaving technology

Woven textile antennas are produced by interlacing conductive and non-conductive fibers using traditional weaving techniques (Fig. 4), enabling precise and stable placement of conductive elements. This structure ensures accurate impedance control, reliable frequency characteristics, and robust signal transmission. Woven antennas offer high mechanical strength and resistance to deformation, supporting long-term performance. However, they are less flexible than knitted or embroidered antennas, which may reduce wearing comfort. Additionally, the weaving process is complex, requiring specialized equipment and skilled operators.

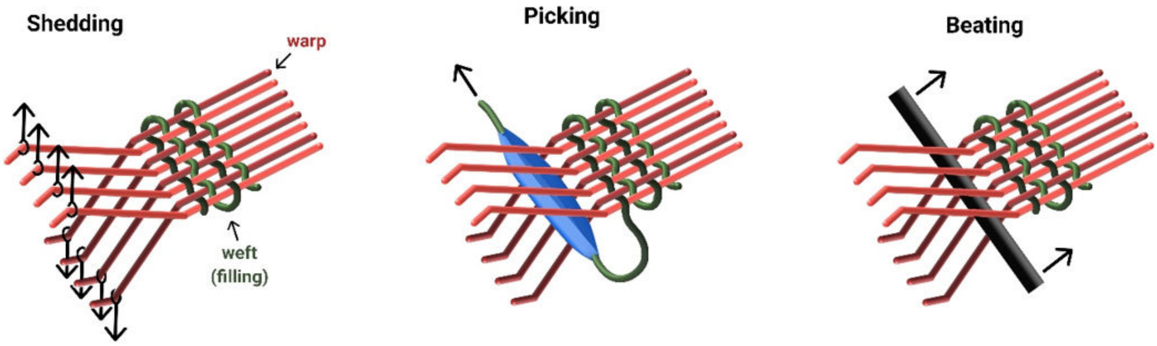

Fig. 4. Principle of weaving technology.

Technologies for contacting of textile antennas

Soldering

Soldering joins the metal fibers of a textile antenna to an SMA connector or coaxial cable using heat, forming a strong electrical bond. This method is suitable for temperature-resistant materials; however, heat-sensitive textiles often require protective surface treatments to prevent thermal damage. Additionally, soldered joints can be brittle, so encapsulation is recommended to improve mechanical stability.

Sewing

Contacting textile antennas with interposers or PCBs can be achieved by sewing conductive thread through metallised vias. This method requires no specialised equipment, offering a low-cost, accessible solution. However, friction between the thread and PCB edges may lead to mechanical wear, thread loosening, and eventual contact instability.

Resistance and ultrasonic welding

Welding joins metal components using heat, with resistance and ultrasonic welding commonly applied for textile antenna integration. In resistance welding, heat is generated by electric current through electrodes, forming solid electrical connections without external wires or solder. Encapsulation can enhance contact durability. Hot bar resistance welding (Fig. 5) is particularly suited for creating robust, wire-free joints. Ultrasonic welding employs high-frequency mechanical vibrations to locally melt materials at the contact surface, forming strong bonds. A thermoplastic polyurethane (TPU) film is typically used to facilitate contact. The process is fast and precise, with heat generation confined to the weld zone, minimizing thermal damage to surrounding textile materials. Vibrations (20–40 kHz) are delivered from a generator through a sonotrode to the joining surfaces, enabling efficient and controlled welding.

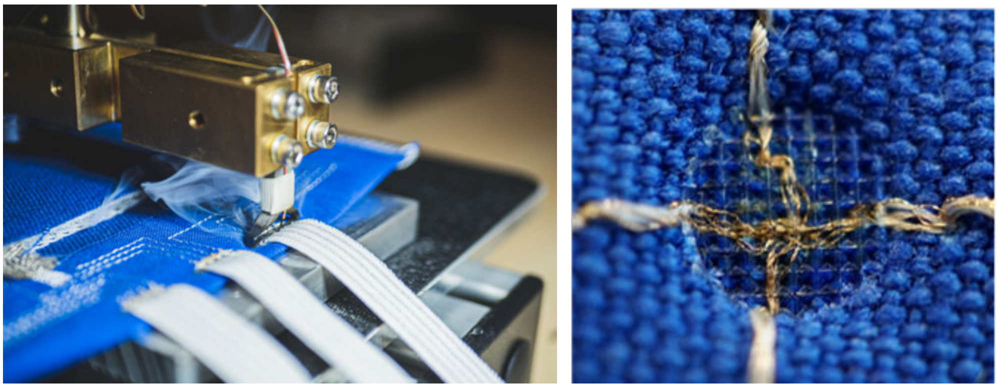

Fig. 5. Hot bar spot welding and ultrasonic welded conductive threads.

Adhesive bonding

Adhesive bonding (Fig. 6) preserves the flexibility and comfort of textiles by avoiding mechanical stress and high temperatures, unlike welding methods. It enables the joining of diverse textile and conductive materials on various surfaces. However, adhesives, particularly conductive types, may degrade over time due to washing or mechanical stress, and some require extended curing periods to achieve full strength.

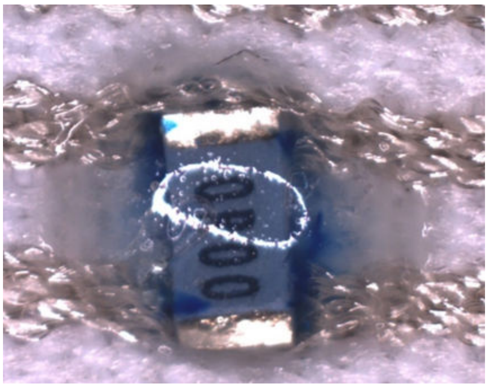

Fig. 6. SMD resistor connected using contact technology based on UV curable non-conductive adhesive on a textile ribbon.

Thermo-compression bonding

Thermo-compression bonding combines heat and pressure to form strong, stable mechanical and electrical connections between materials. Widely used in electronics, microtechnology, and e-textiles, it enables reliable bonding of dissimilar materials, such as conductive elements and textiles, where long-term durability is essential. In e-textile applications, thermo-compression bonding, prototyped at Fraunhofer IZM, enables simultaneous mechanical and electrical connection in a single step using localised heating. It supports direct bonding to insulated conductors, PCBs, flexible PCBs, SCBs, and various textile circuit types, including woven, knitted, embroidered, and printed structures.

references [16], [17], [18], [19]

EXPERIMENTS AND RESULTS

In the implementation of planar textile antennas, the shapes and design principles of conventional planar antennas, typically fabricated on printed circuit boards using photolithography or printing techniques, are often adopted. However, there are numerous factors that influence the electrical properties and behavior of textile antennas, particularly in terms of resonant frequency, radiation pattern, and impedance characteristics. A key factor may already be the specific method of textile antenna fabrication itself, including the connection technique, the density of conductive threads, the effect of mechanical deformation, as well as environmental influences such as humidity and proximity to the human body. Several of these influencing factors on textile antenna performance have been experimentally investigated. For this purpose, a planar embroidered and knitted bow-tie antenna design was employed as the test structure.

Influence of interconnection

The prepared samples of textile antennas were interconnected using two methods:

- Hot bar spot welding of SMA pigtails (Fig. 7A)
- Hot bar spot welding of printed circuit board (PCB) equipped with soldered U.FL connectors (Fig. 7B)

In the latter case, the PCB was welded from the reverse side of the conductive structure. The PCB itself was designed to provide impedance matching for optimal signal transmission.
A comparison of the conductive structures revealed that the variant incorporating two plaited yarns contained a higher volume of conductive material. This increased conductivity proved advantageous when interconnecting SMA pigtails, where the contact area is relatively small compared to PCB connections. However, the use of two plaited yarns results in reduced elasticity of the knitted structure. Consequently, initial knitting parameters must be carefully adjusted to maintain comparable mechanical flexibility.
Despite the lower conductive content, the configuration using a single yarn of hybrid thread, when combined with PCB interconnection, demonstrated superior performance in terms of lower reflection coefficient (S_{11} attenuation), as illustrated in Fig. 8.

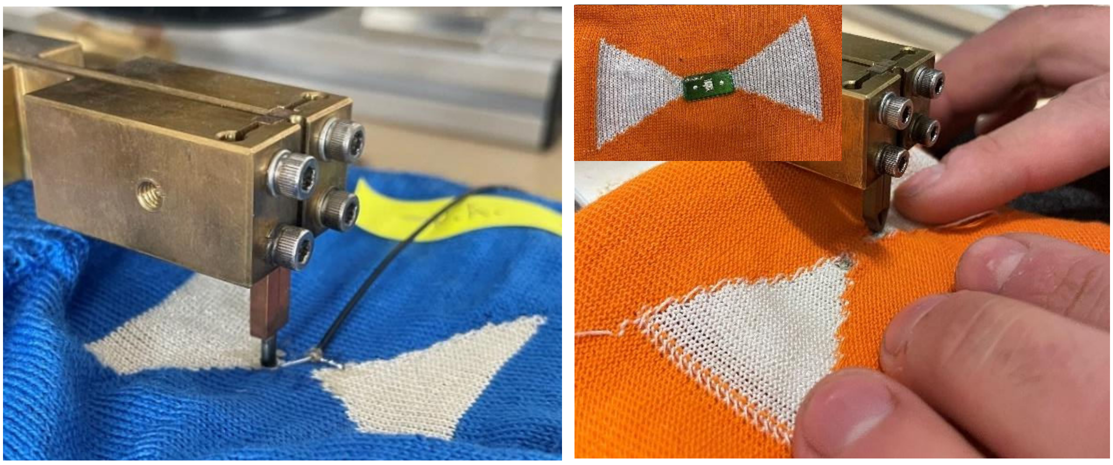

Fig. 7. (A) Hot bar spot welding of SMA pigtail and (B) PCB hot bar spot welding.

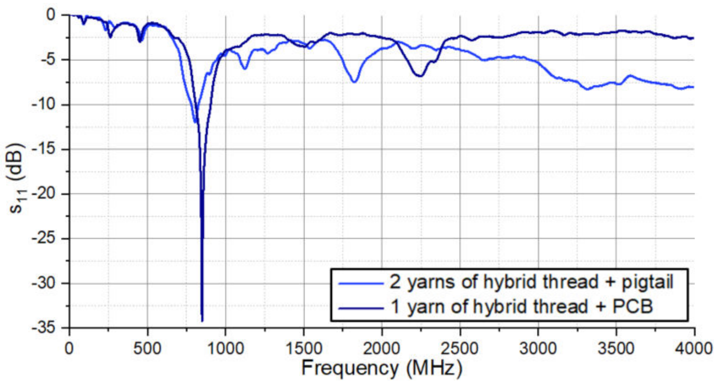

Fig. 8. Difference in interconnecting technology and conductive structure.

Influence of embroidering densities

In the fabrication of planar textile antennas using embroidery technology, both the density and stitching pattern of the conductive antenna surface can be precisely controlled. Figure 9 presents four variations of embroidered bow-tie antennas, each featuring a different density of conductive threads used to form the planar conductive area of the antenna.
The corresponding measured reflection coefficient (S_{11} parameter) for these textile antennas is shown in Fig. 10. The results clearly demonstrate the influence of embroidery density on the resonant frequency of the antennas. Higher thread densities typically result in lower surface resistivity and improved conductivity of the radiating elements and together with change of capacity, can lead to shift in resonant frequency.
These findings underscore the importance of optimizing embroidery parameters, not only for mechanical flexibility and integration into garments but also for maintaining desired electromagnetic performance. This tunability via embroidery parameters provides a valuable degree of freedom in the design of wearable textile antennas, especially when balancing electrical performance with textile integration requirements.

Fig. 9. Bow-tie antennas with different embroidering densities.

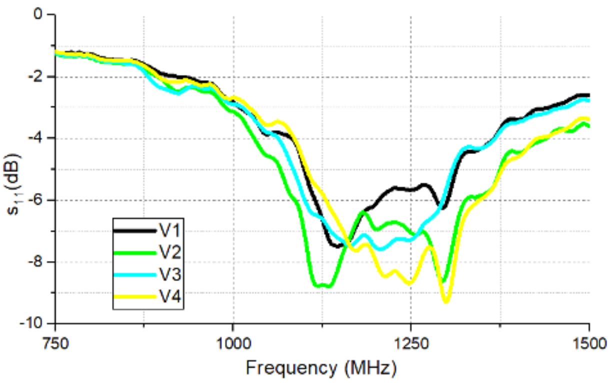

Fig. 10. S_{11} parameters of embroidered antennas for different embroidering densities.

Influence of textile antenna stretching

Knitted textile antenna samples were mounted in a custom-designed fixture (Fig. 11), which enables the antenna to be suspended in air and mechanically stretched in a controlled manner. Measurements were conducted using a LeCroy SPARQ-3002E vector network analyzer, with frequency characterization performed up to 4 GHz.
Each antenna sample was incrementally elongated in 10 mm steps, up to the maximum achievable extension permitted by the limitations of the interconnection method and the mechanical properties of the textile substrate. The maximum elongation reached was approximately 140% of the original length. At each elongation step, the reflection coefficient (S_{11}) was recorded.
The results demonstrate a clear correlation between mechanical elongation and the antenna's electromagnetic behavior. Specifically, the resonant frequency exhibited a downward shift with increasing elongation, as shown in Figure 12. This behavior can be attributed to the elongation-induced changes in the physical dimensions of the radiating elements and the distribution of conductive material, which affect the effective electrical length of the antenna. These observations highlight the importance of accounting for mechanical deformation in the design and integration of stretchable textile antennas, especially in wearable applications where dynamic deformation is expected during use.

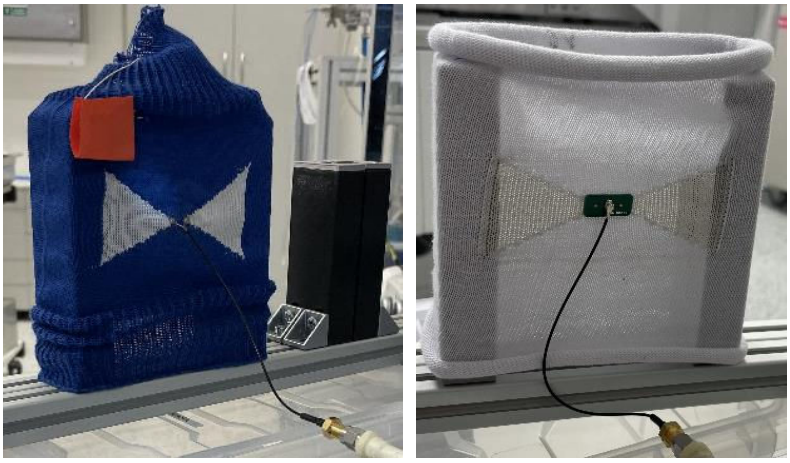

Fig. 11. Stretching of textile antennas.

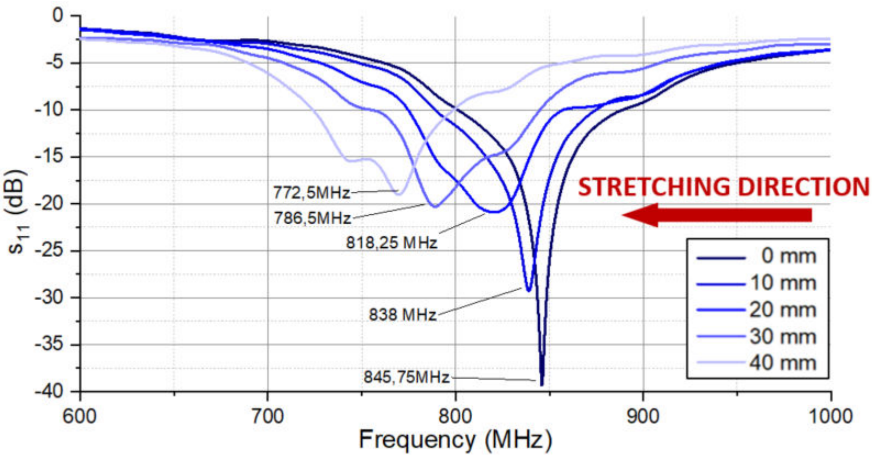

Fig. 12. Dependence of resonant frequency on stretching with step 10 mm.

Data transmission verification

Textile antennas have garnered significant research interest for use in Industrial, Scientific, and Medical (ISM) bands, particularly at 2.4 GHz for Bluetooth and Wi-Fi, as well as in the sub-GHz range (e.g., 868 MHz) for Low Power Wide Area Networks (LPWAN) and LoRa-based communication systems. These frequency bands are highly relevant for applications such as wearable communications, physiological monitoring, and passive wireless sensor networks.

As illustrated in Figure 13, the measured reflection coefficient (S_{11}) of the embroidered bow-tie antenna confirms a distinct resonance at 868 MHz, validating its applicability for LoRa and LPWAN applications. The observed return loss indicates effective impedance matching, resulting in minimal signal reflection and efficient RF power transmission within the target frequency band.

While these results highlight the functional potential of embroidered textile antennas, further optimization is necessary to address challenges related to electromagnetic stability, mechanical robustness under deformation, and environmental resilience, particularly in real-world wearable and mobile environments where the antenna may be subjected to moisture, bending, and mechanical stress.

To verify and demonstrate the data transmission capabilities of textile antennas, a dedicated, modular, and flexible Internet of Things (IoT) prototyping platform was designed and developer (Fig. 14). This platform supports the integration, testing, and evaluation of textile-based electronics and smart fabric systems in a wearable context.

The system architecture includes wireless communication capabilities, power management components, and textile-compatible interconnects, enabling a systematic and scalable approach to prototyping wearable IoT devices. At its core is an ESP32-based microcontroller unit (MCU), chosen for its integrated Wi-Fi and Bluetooth connectivity. The power subsystem features an advanced Battery Management System (BMS) utilizing the BQ25628 charging IC, along with dual TPS63100 DC-DC converters, providing a stable and efficient power supply suitable for RF communication modules, sensor nodes, and embedded textile circuits - including bow-tie textile antennas.

To support robust and discreet electrical interfacing, flexible conductive textile ribbons have been implemented. These include four-conductor stretchable variants that enable seamless integration of sensors and addressable LEDs. This textile-compatible interconnection strategy enhances the mechanical resilience and aesthetic integration of functional electronics into fabric-based systems, thereby advancing the development of wearable smart textiles.

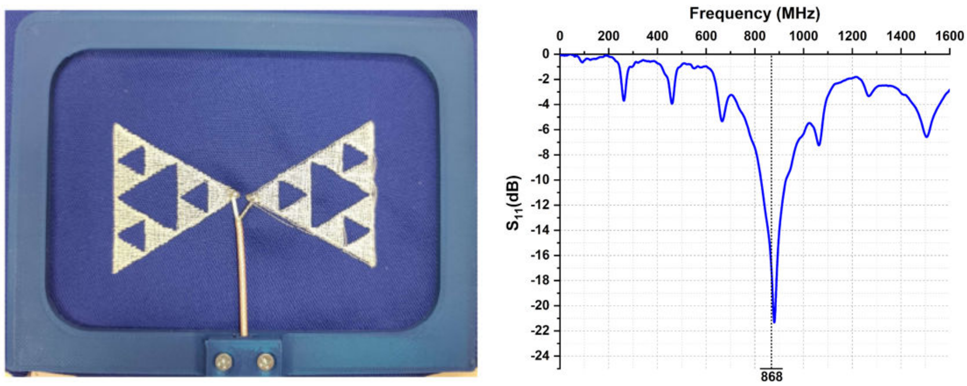

Fig. 13. Embroidered bow-tie textile antenna and its measured S_{11} parameter.

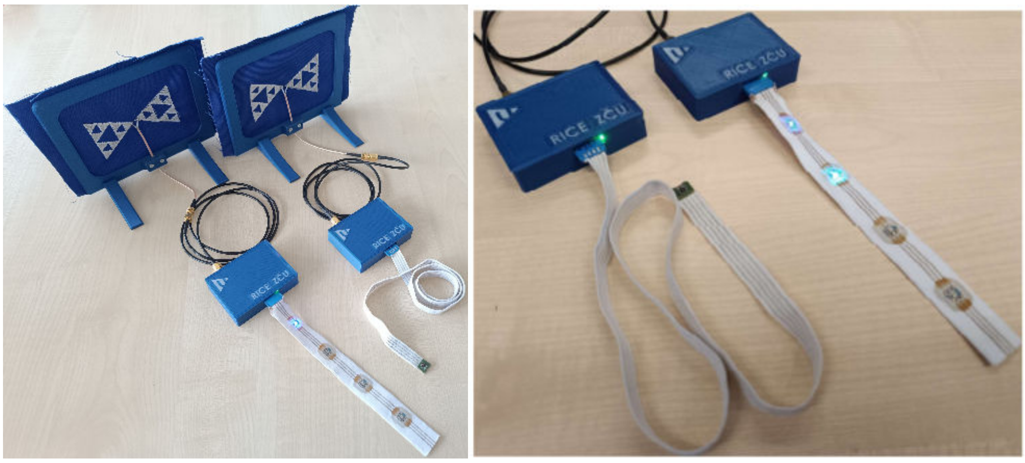

Fig. 14. The platform with textile antenna for data transmission.

SUMMARY AND CONCLUSIONS

This paper provides a comprehensive analysis of the key technologies used in the fabrication and integration of wearable textile antennas employing hybrid conductive threads. Various textile manufacturing techniques, including knitting, embroidery, weaving, and printing, are examined, each offering specific advantages and trade-offs depending on the target application, required mechanical properties, and desired electromagnetic performance.

A critical aspect of textile antenna design lies in the choice of interconnection techniques, which significantly influence the overall reliability, signal integrity, and long-term functionality of the system. Methods such as hot-bar welding, ultrasonic welding, thermo-compression bonding, and adhesive lamination are evaluated in terms of their electrical performance, mechanical robustness, and compatibility with textile substrates. The selection of an appropriate interconnection strategy must address not only electrical and structural requirements but also practical considerations such as wearability, washability, and durability under repeated mechanical stress and environmental exposure.

Textile antennas, unlike their rigid counterparts, offer unique benefits including mechanical flexibility, low weight, and the potential for seamless integration into garments. These characteristics make them highly attractive for emerging applications in wearable Internet of Things (IoT), ISM-band wireless communications, and passive sensing. However, the radio-frequency (RF) performance of textile antennas is inherently sensitive to mechanical deformation, moisture, and variability in the surface conductivity of the textile medium. These challenges necessitate the development of advanced materials, optimized antenna geometries, and stable fabrication techniques.

Ongoing research into hybrid conductive materials, multilayer textile laminates, and robust fabrication processes continues to advance the field, improving the repeatability, electromagnetic stability, and operational lifespan of embroidered and flexible textile antennas. These innovations are essential to enable the reliable deployment of next-generation wearable RF and IoT systems in real-world environments.

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REFERENCES

[1] M. Radouchova, S. Suchy, and T. Blecha, 'Embroidered Flexible Elastic Textile Antenna as Strain Sensor', Proc. Int. Spring Semin. Electron. Technol., vol. 2022-May, 2022.

[2] D. Patron et al., 'On the Use of Knitted Antennas and Inductively Coupled RFID Tags for Wearable Applications', IEEE Trans. Biomed. Circuits Syst., vol. 10, no. 6, pp. 1047–1057, 2016.

[3] Y. Liu, A. Levitt, C. Kara, C. Sahin, G. Dion, and K. R. Dandekar, 'An improved design of wearable strain sensor based on knitted RFID technology', 2016 IEEE Conf. Antenna Meas. Appl. CAMA 2016, 2017.

[4] M. A. S. Tajin, C. E. Amanatides, G. Dion, and K. R. Dandekar, 'Passive UHF RFID-Based Knitted Wearable Compression Sensor', IEEE Internet Things J., vol. 8, no. 17, pp. 13763–13773, 2021.

[5] M. Radouchova and T. Blecha, 'Highly Elastic Textile Conductive Ribbons as Frequency Resonators for Wearable Strain Monitoring', Proc. Int. Spring Semin. Electron. Technol., vol. 2024, pp. 1–5, 2024.

[6] Yohandri, F. Al Haqqi, and A. Munir, 'Design of a Flexible Antenna Using Weaving Technique for C-Band Applications', IEEE Antennas Propag. Soc. AP-S Int. Symp., vol. 2023-July, no. 1, pp. 181–182, 2023.

[7] M. Fernandez, C. Vazquez, and S. Ver Hoeye, '2.4 GHz Fully Woven Textile-Integrated Circularly Polarized Rectenna for Wireless Power Transfer Applications', IEEE Access, vol. 12, no. July, pp. 89836–89844, 2024.

[8] A. P. Ghodake and B. G. Hogade, 'Textile Antenna -Structure, Material and Applications', Proc. Int. Conf. Electron. Renew. Syst. ICEARS 2022, no. Icears, pp. 1855–1860, 2022.

[9] U. Hasni and E. Topsakal, 'Wearable Antennas for On-Body Motion Detection', 2020 Usn. Radio Sci. Meet. (Joint with AP-S Symp. Usn. 2020 - Proc., pp. 21–22, 2020.

[10] I. Ibanez Labiano, D. Arslan, E. Ozden Yenigun, A. Asadi, H. Cebeci, and A. Alomainy, 'Screen Printing Carbon Nanotubes Textiles Antennas for Smart Wearables', Sensors (Basel)., vol. 21, no. 14, 2021.

[11] S. Suchý, D. Kalaš, J. Kalčík, and R. Soukup, 'A Comparison of Resistance Spot and Ultrasonic Welding of Hybrid Conductive Threads', *3rd Int. Spring Semin. Electron. Technol.*, pp. 1–5, 2020.

[12] J. Pei, J. Fan, and R. Zheng, 'Protecting Wearable UHF RFID Tags with Electro-Textile Antennas: The challenge of machine washability', *IEEE Antennas Propag. Mag.*, vol. 63, no. 4, pp. 43–50, 2021.

[13] D. Kalas, J. Kalcik, J. Reboun, R. Soukup, and A. Hamacek, 'Stretch Testing of SMD Resistors Contacted by a Novel Thermo-compression Method on a Textile Ribbon', *Proc. Int. Spring Semin. Electron. Technol.*, vol. 2021-May, May 2021.

[14] K. Garbacz, L. Stagun, S. Rotzler, M. Semenec, and M. von Krshiwoblozki, 'Modular E-Textile Toolkit for Prototyping and Manufacturing', no. January, p. 5, 2021.

[15] 'E-Textile Bonding'. [Online]. Available: https://www.izm.fraunhofer.de/en/abteilungen/system_integrationinterconnectiontechnologies/leistungsangebot/prozess- _und_produktentwicklung/nca-bonding-interconnection-process-fore-textiles.html.

[16] Blecha, T.; Moravcova, D.; Soukup, R. Electronic textiles. In Advances in Chemical Engineering. Rethinking Manufacturing: Next Generation Sensors and Devices by Microfabrication. London: Elsevier, 2024, s. 1-72. ISBN 978-0-443-31586-2

[17] R. Polanský *et al.*, 'A novel large-area embroidered temperature sensor based on an innovative hybrid resistive thread', *Sensors Actuators, A Phys.*, vol. 265, no. August, pp. 111–119, 2017.

[18] L. Xu et al., "Characterization and Modeling of Embroidered NFC Coil Antennas for Wearable Applications," *IEEE Sens. J.*, vol. 20, no. 23, pp. 14501–14513, 2020.

[19] H. He, X. Chen, L. Ukkonen, and J. Virkki, "Clothing-integrated passive RFID strain sensor platform for body movement-based controlling," *IEEE Int. Conf. RFID Technol. Appl. (RFID-TA)*, pp. 236–239, 2019.